THE IMPACT OF GRADE ENGINEERING® ON SAG MILLING

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ABSTRACT

In addition to minerals displaying variations in grade within an ore body, blasted rock often concentrates particular minerals preferentially into finer size fractions. Grade engineering strategies seek to exploit intrinsic heterogeneity and grade variability to improve the viability of operations experiencing declining grades and unit metal productivity. Examples may include processing coarse and fine material separately or selectively rejecting or sorting particular size classes. Since SAG circuits are almost universal in the industry, strategies are required for operating these circuits on altered feed size distributions and variable feed properties. Circuits should be operated to maximise productivity by leveraging variability with flexible strategies.

This paper evaluates the performance of SAG milling on scalped feeds and outlines operating and design processing strategies that can provide the necessary flexibility to maintain optimal performance in the context of varying size and ore properties. Grade engineering strategies that involve pre-screening and rejecting a coarse low-grade component may alter current SAG milling performance if the coarse rock content in the feed becomes too small. Although it is possible to increase the ball load to compensate for the reduction in large rocks, it can become difficult to maintain sufficient load within the mill, media costs increase and extra ball milling capacity is required. Therefore if preconcentration removes the coarse, competent fraction from the SAG mill feed, different operating strategies will be required.

In addition to natural grade by size responses grade engineering strategies highlight the bench scale heterogeneity. If measured for each processing ore type, variability of grade and competence can be used to control the process and maintain operation at peak performance. Potential solutions for SAG mill operation within grade engineered circuits will be presented, thus reducing the barriers to implementation of these novel strategies.

KEYWORDS

Grade Engineering®, preconcentration, flexible circuit design

INTRODUCTION

The mining industry is facing several technical, economic, social and environmental challenges affecting profitability and sustainability (Bearman, 2012; Franks et al., 2012; Prior et al., 2012; Topp et al., 2008). The need to meet metal demand at higher operating costs coupled with volatility in commodity prices are of increasing concern. The mining industry has reacted to this complex scenario by reducing ore cut-off grade and converting additional resources into reserves. This has resulted in increased revenues but at higher production costs with marginal profitability improvement. This trend has been sustained by high commodity prices which also have exaggerated capital intensity and labour inputs. This pattern is clearly evident for countries such as Australia, Canada and Chile, (Figure 1), where mining constitutes an important part of GDP.

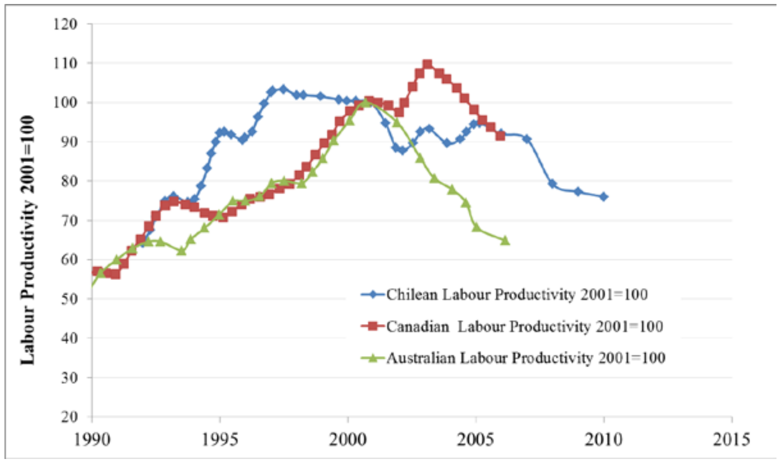


Figure 1 - Australian, Canadian, and Chilean labour mining productivity (Carrasco, 2014).

The drivers behind the dramatic decline in mining productivity have been higher prices combined with the depletion of near surface, high-grade ore bodies which have attracted an increased investment in mining lower-grade deposits (Topp et al., 2008). Lower head grades generate more mineable waste and increased processing tonnage to produce equivalent metal, resulting in lower mining productivity. As head grades continue to decline, production costs will continue to rise making this strategy vulnerable to lower commodity prices. By exploiting innovations and technologies that can support larger scale material movement and mineral processing, the industry has been able to increase annual metal production even while feed grades have declined over time (Figure 2) (Access Economics, 2008).

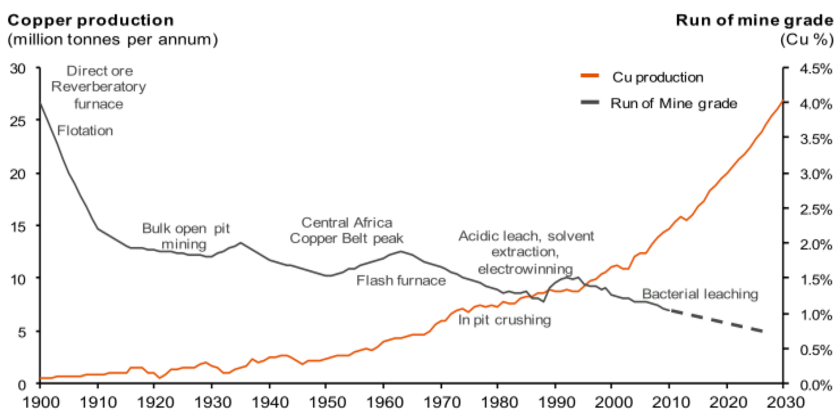


Figure 2 - Copper production and run of mine copper grades since 1900 and introduction of mining and processing technologies. Reprinted from Mackenzie (2011).

An unwelcome consequence of decreasing head grades is an increase in energy consumption (Figure 3) and therefore unit metal production cost (Noergate & Haque, 2010; Norgate & Jahanshani, 2010; Norgate et al., 2007). Lower head grades require more comminution and grinding energy to reach an adequate level of liberation for recovery.

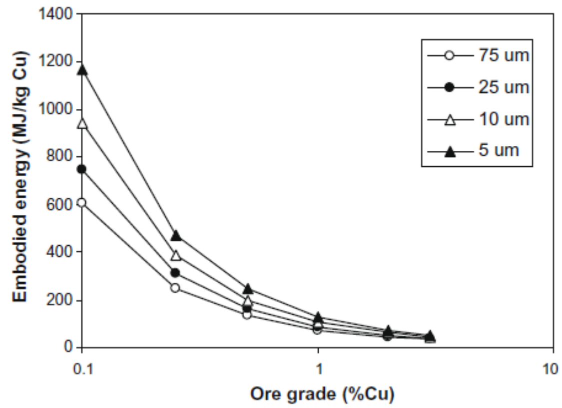


Figure 3 - Effect of ore grade and grind size on embodied energy copper production during concentrating and smelting. Reprinted from Norgate & Jahanshani (2010).

Approximately one third of the energy consumed in typical copper and gold mining operations is expended in crushing and grinding ore to feed into conventional recovery processes (Ballantyne and Powell, 2014). With lower feed grade ores, much of this energy is directed towards breaking already barren particles. The cost of grinding the entire process stream to the final target grind size increases exponentially as the grade decreases and liberation size becomes smaller (Norgate & Jahanshani, 2010). To overcome this trend, the mining industry needs to focus on finding new technologies and operational strategies to increase extraction and energy efficiency.

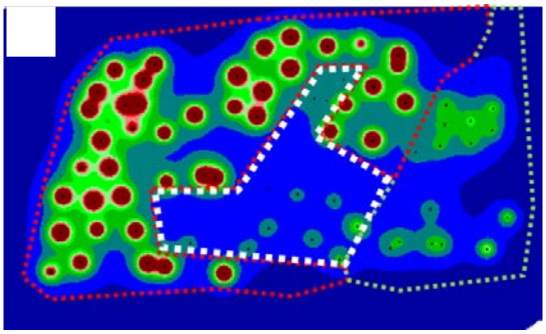
Grade Engineering® to address mining productivity challenges

Early gangue rejection and pre-concentration of ores prior to the energy-intensive milling stages of comminution has been identified as a feasible technical alternative whereby metal productivity and efficiency can be improved (The AusIMM, 2015, Carrasco et al., 2015, Bowman and Bearman 2014,Carrasco et al., 2014, Carrasco, 2013,Bearman, 2012, Logan and Krishnan 2012, Bamber, 2008a; Bamber et al., 2008b, Bamber et al., 2006a, Bamber et al., 2006b).

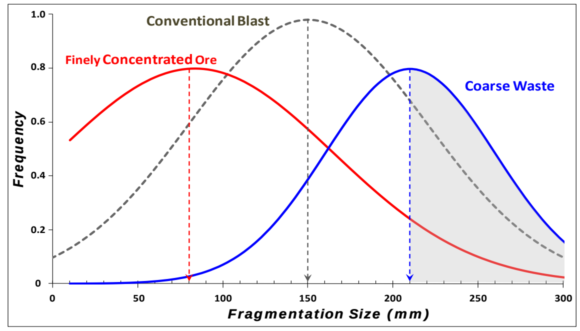
Grade Engineering (The AusIMM 2015, CRCORE 2015,b, Mining Magazine, 2014) involves a range of integrated technologies and operating strategies for improving concentrator feed grades through early coarse rejection of low value components prior to the more capital and operating cost-intensive processing activities. Grade Engineering provides additional operational leverage enabling dynamic management of short term production constraints, expansions and bottlenecks over life of mine with less reliance on major capital investments. Grade Engineering has been successfully applied to a range of different deposit styles, resulting in an estimated potential increase of +1US$ billion in net cash flow (CRCORE, 2015b). Up to five coarse separation strategies are available for removing coarse low-grade rock: differential blasting based on grade, pre-screening to exploit preferential grade by size deportment, coarse gravity separation, and sensor-based sorting based on mass and streams. Two of these are considered in this work: differential blasting for grade and preferential grade by size deportment.

Differential blasting for grade

Differential blasting for grade is designed to exploit in-situ grade variability for material normally assigned a single destination (i.e. waste, leach, and concentrator). Assays from blast-hole drilling are integrated with a blast design that increases energy and generates a fine particle size distribution in areas of higher grade while in the lower grade areas the blast is conditioned to result in a coarse particle size distribution. Metal grade will therefore concentrate in finer size fractions and a screening process will be able to separate high grade from low grade material (Figure 4).



(a)



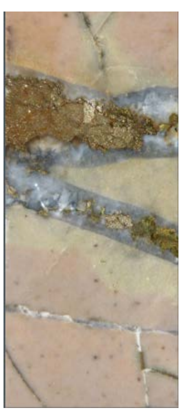
(b)

Figure 4 – a) Illustration of application of high energy blast applied to high grade material. b). Bimodal particle size distribution as a result of differential blasting.

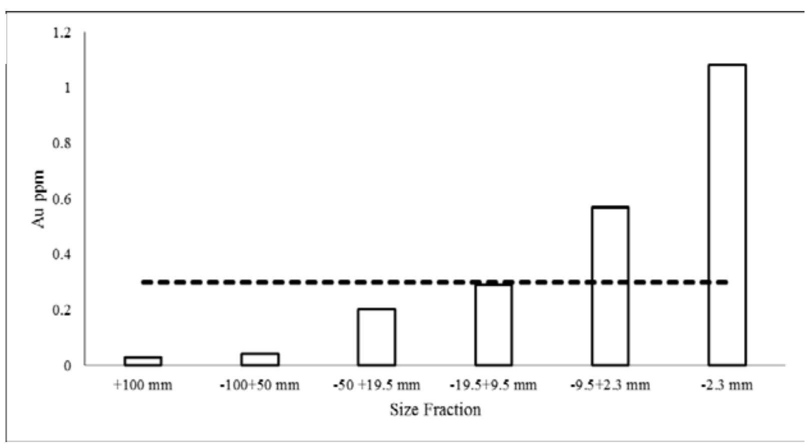
Differential blasting for grade has been applied to a reef-style precious metal open pit operation. During the trial, screening of blast conditioned ROM feed resulted in a doubling of the grade received by the SAG mill. This also resulted in increased unit metal productivity and energy efficiency (CRCORE, 2015).

Preferential grade by size deportment

This concept is used to define the propensity of some ores to preferentially deport metal in specific size fractions (Carrasco et al., 2015; Carrasco et al., 2014; Carrasco, 2013). Unlike differential blasting, this is a function of geological characteristics of mineralisation. Rock types with vein mineralisation style (Figure 5,a) will exhibit a stronger preferential grade by size response relative to a disseminated dominant mineralisation. Figure 5,b depicts a SAG feed belt cut sample from an Australian Au-mine operation, where Au grade is significantly biased towards small size fractions. Although this sample was defined as waste (feed grade 0.26 ppm < cut-off 0.3 ppm) the use of screening could extract ore from the original waste sample (Figure 5,b -9.5+2.3 mm, -2.3 mm).



(a)



(b)

Figure 5 – a) Example of style of mineralisation whereby metal is preferentially concentrated in finer fractions. b) Belt cut grade by size raw data in an operation with a waste-ore cut-off of 0.3 ppm (dotted line). There are certain size fractions that can be classified as ore.

Differential grade by size and preferential grade by size deportment share a key piece of exploitation equipment: a screen. In current practice, each minimum mining unit of ore in the pit is assigned a single destination on the basis of average grade. Grade Engineering-based separation on intra-unit scale is able to deliver separated ore to multiple processing destinations. Figure 6 shows an example of a Grade Engineering circuit depicting material assigned with the destinations “Leach” and “Waste” by means of grade by size response exploitation by screening. Metallurgical attributes of the separate streams generated by employing Grade Engineering will have different characteristics. In addition to grade, particle size distribution will be altered. Comminution strategies will need to be properly tuned to effectively process the Grade Engineering streams.

SAG mill response to feed particle size

Semi-autogenous mill performance is greatly affected by the proportion of coarse rocks in the feed that combine with the balls to impart breakage energy to the mill contents. To a lesser extent, the feed size distribution also determines the proportion of ‘critical size’ material in the mill which is both too small to act as breakage media and too large to be broken at high rates. Since the preconcentration strategy employed by Grade Engineering involves the use of a screen, the inherent result is an altered size distribution entering the comminution circuit, this can have significant downstream effects if the first stage of comminution is performed by a SAG mill. Design and operating strategies need to be developed to counter the potential impact that this can cause on the performance of SAG mill circuits. This will also enable Grade Engineered circuits to fully extract the benefits of lower energy consumption and increased downstream recovery.

METHODOLOGY

The impact of Grade Engineering on comminution circuits incorporating SAG mills was based on a range of calculated size distributions from a fully integrated Grade Engineering optimization over the Life of Mine (LOM). Grade Engineering attributes were populated into the long term block model and the financial analysis included operating costs, capital costs and processing performance. JKSimMet has been used to simulate the achievable throughputs from the altered size distributions. Both Grade Engineering and comminution circuit modelling were kept separate in this analysis to quantify the effect of the variable feed size on circuit throughput. Limitations in the equipment models within JKSimMet need to be considered in the simulation process. For instance, the variable rates SAG mill model is fitted on a large database of surveyed mills globally. Although this is a strength in most other applications of the model, this limits the model in this case because the model database lacks such fine feed size distributions so the rates scaling is not accurate. For the finest size distribution evaluated, data from only one similar operation was available to the authors and this was used to modify the grinding rates to obtain a more realistic response. To obtain realistic responses within the ball milling circuit, the recirculating load and P_{80} were constrained to 500% and 180 µm respectively. To maintain the rock load in the SAG mill with the fine feed scenarios, the ball load was increased and the pebble ports were closed.

The results and limitations of this analysis were used to frame further investigation into potential operating strategies that would improve controllability. Two blending strategies were employed to investigate the effect on performance. One involved the blending of all the 14 areas assessed, while the other was aimed at integrating the Grade Engineering circuit with the comminution circuit and allow independent control over the proportion of coarse and fine rock in the feed to the SAG mill. The design of such a circuit was also evaluated to investigate options for simplifying the circuit layout as it was identified that pre-crushing circuits can result in large footprints.

RESULTS

The Grade Engineering assessment was conducted on 14 potential production areas at a copper/gold mine. The potential of each area was estimated and a financial optimisation study was conducted to determine what proportion of the production area would pass through the Grade Engineering circuit and what proportion could be sent directly to the mill through the primary crusher (see Figure 6). For three areas it was more financially advantageous to send the whole production area directly to the mill without passing through the Grade Engineering circuit; for six areas all the material was screened prior to milling and for the final five areas, a range of splits were determined (see Table 1). These decisions are determined by the grade of block, Grade Engineering response rank and the ability to increase value. The long term economic optimisation did not take into account the potential short term disturbances at short term scale. The Grade Engineering analysis disregarded short term milling and downstream disturbances and showed that it was economically advantageous. At the current throughput rate of the comminution circuit, these blocks represent approximately 500 hours of production. The variability in feed size distribution over this time will clearly impact the performance of the SAG mill as the proportion above 100 mm varies between 0% and 29%. Additionally, the variability in the proportion of material below 1 mm (1% - 18%) is likely to significantly impact the operating strategy employed for the ball mills.

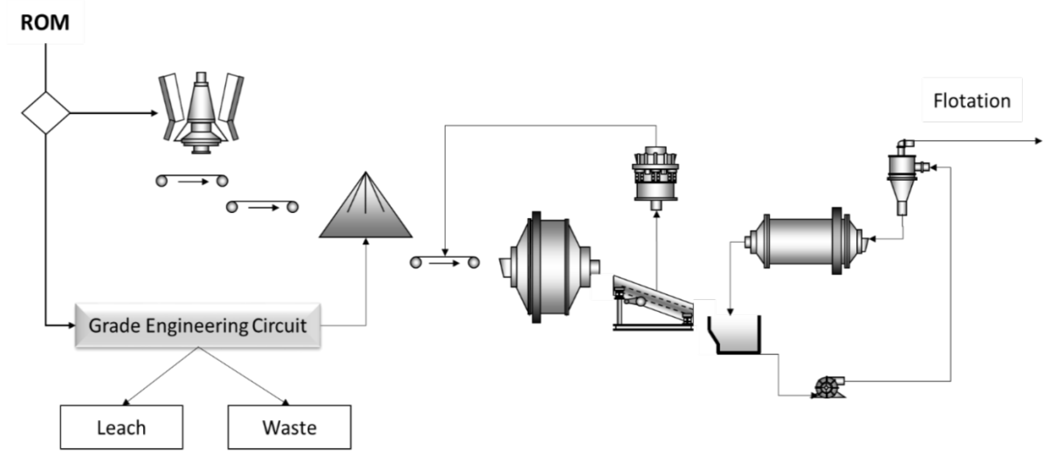


Figure 6 - Circuit Analysed.

Table 1 – Blast blocks assessed for grade engineering potential. The blocks that were simulated through the comminution circuit are highlighted.

Production area	Volume (t)	% Direct Mill Feed	% Grade Engineered	% -1mm	% +100mm
1	43,875	0	100	7	29
2	**122,625**	**61**	**39**	**3**	**23**
3	**52,875**	**100**	**0**	**1**	**19**
4	**22,500**	**100**	**0**	**1**	**19**
5	**24,750**	**100**	**0**	**1**	**19**
6	30,375	0	100	7	29
7	46,125	0	100	6	25
8	**180,000**	**17**	**83**	**7**	**3**
9	**120,375**	**49**	**51**	**9**	**9**
10	124,875	28	72	4	27
11	**84,375**	**4**	**96**	**18**	**1**
12	82,125	0	100	6	25
13	16,875	0	100	14	0
14	158,625	0	100	7	16

The full size distributions of the simulated products resulting from the addition of the Grade Engineering circuit product and the direct mill feed component are shown in Figure 7. These size distributions show a large degree of variation between the blocks; from 100% passing 30 mm to material greater than 250 mm. The variability between these size distributions necessitates different processing strategies, especially if these changes occur over short periods of time.

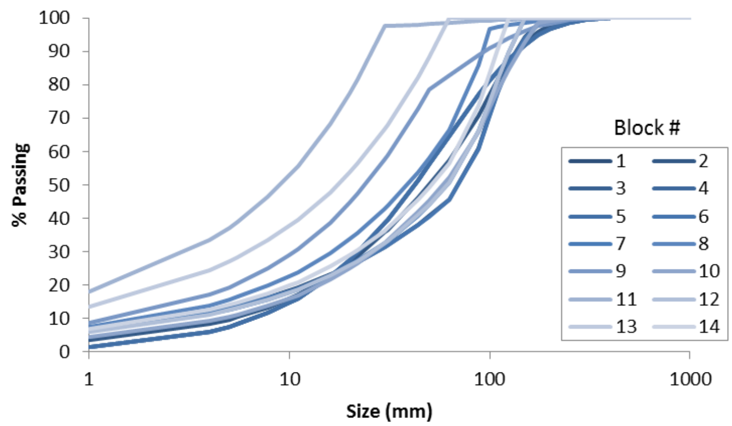


Figure 7 - Grade engineered product size distributions.

JKSimMet software was used to simulate the performance of the circuit in Figure 6 in response to the feed size distributions highlighted in Table 1. The results from these simulations are shown in Figure 8. The base case with 100% direct feed showed the lowest throughput response (bench 3) and Grade Engineered feed size distributions had a positive impact on circuit throughput. The throughput response was found to be closely related to the proportion of - 1 mm material in the feed, increasing at a rate of 113 t/h per 1% increase in - 1 mm material.

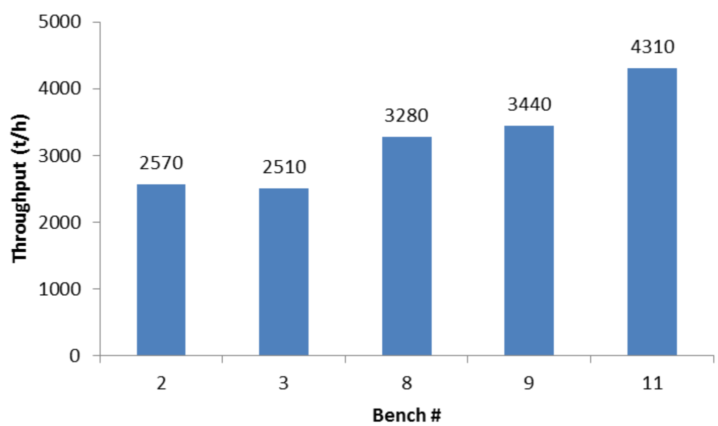


Figure 8 – Throughput response of comminution circuit to each bench.

Using the relationship developed between %-1 mm material in the feed and throughput, the throughput expectations were calculated for the other benches in the Grade Engineering analysis. Figure 9 displays the estimated throughput for each block and the time period that that block will run for based on the size of the block.

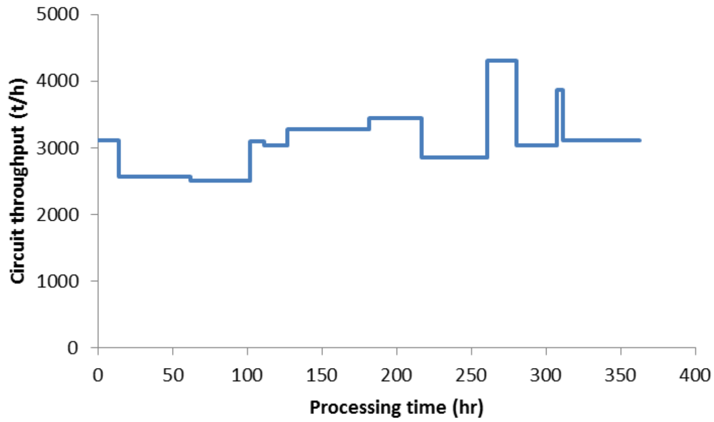


Figure 9 – Throughput expectation over time if blocks are processed in numerical order.

The variance between the blocks can be substantial, for instance when block 11 is processed the throughput increases by 1500t/h and then back down over a 20 hour period. To maintain the ore load within the mill, the ball load was increased and the pebble ports were closed in the simulations, a control strategy that would not be able to deal with the frequency of this variation. Six possible strategies were identified that could be employed to reduce this variance:

1. blending similar blocks (fine, medium or coarse)
2. blending dissimilar blocks (fine with coarse)
3. blending based on a property other than the feed size distribution
4. pre-crush the direct feed and convert the SAG mill to a AG mill
5. stockpile Grade-Engineered product and feed independently to direct mill feed material
6. integrate Grade-Engineering circuit with comminution circuit.

Mill filling

As the feed size and required SAG mill feedrate vary with the different blocks and degree of removal of coarse sub-grade ore, the mill filling will vary. Mill filling not only affects the available mill power and thus product size, but also the position of the toe of the charge. The trajectory of rocks and balls in the mill is determined by the mill speed and shell liner design, so non-optimal impacting conditions can arise especially if the mill load drops below the design level. A simple illustration of this effect is provided in Figure 10, where a reduction of mill filling from 27% to 21% will result in direct impacting of ball on the mill shell. If the mill can be slowed down this will resolve the impacting issue (shown by the lower trajectory) but reduce milling capacity, if the mill can't be slowed then the mill cannot be viably operated under these ore feed conditions. This results in a hard constraint on mill operation and viable feed distributions that must be accounted for when dealing with a wide variation in possible feed scenarios.

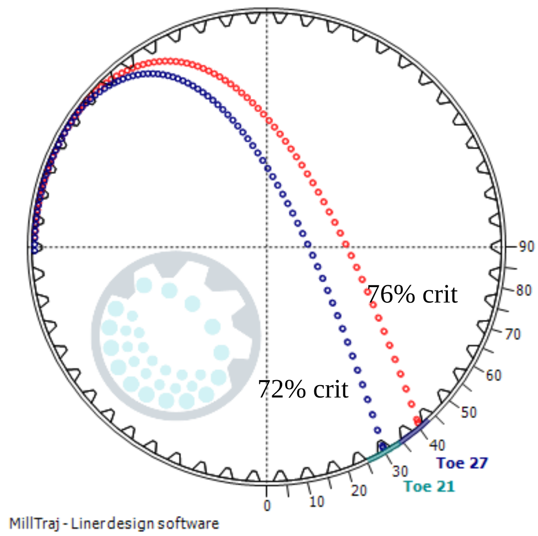


Figure 10 - Outmost ball trajectory impacting on the toe for 27% filling and on the shell for 21% filling

DISCUSSION

Due to the widespread use of SAG mills in the processing of large low-grade deposits and their sensitivity to variations in feed size distribution, additional measures are needed to ensure the controllability of Grade Engineering circuits. Grade Engineering strategies utilise natural and induce grade heterogeneity to increase the profitability of the mine, but processing stability must also be addressed. The simplest strategies to employ are pre-crushing or a blending strategy based on the proportion of the block that will undergo Grade Engineering as an indicator for the fineness of the feed. The form this blending strategy could take would depend fully on the design and location of the Grade Engineering facility and the method of ore transport (trucks or conveyors). But a more nuanced design strategy could be employed to improve the flexible operation of the comminution circuit.

Enabling the ability to independently feed the SAG mill with different proportions of fine and coarse rock will greatly improve the controllability of the comminution circuit. This can be achieved using two methods, either the Grade Engineering product can be stockpiled and fed separately, or the screen can be integrated into the comminution circuit, taking advantage of the size split. This second option is more appealing because it would allow the coarse, middling and fine streams to be fed independently into the SAG mill. The economic feasibility of the options has not been taken into account within this paper, however without the addition of a large number of equipment, the increased capital equipment cost would be marginal, the difference in cost would largely be in materials handling and footprint. The coarse (>100 mm) material could be used to maintain the rock load within the mill, the middlings could be fed to a crusher prior to the mill, greatly reducing the critical size in the load, and the fines could be used to control the throughput and the ball mill recirculating load. This strategy would utilize a slightly larger screening circuit (as even the direct feed material would be screened) and would require either two stockpiles or a split stockpile (coarse and fine physically separated). The flexible flowsheet that was designed allowed coarse and fine to be sent independently to the SAG mill as well as allowing options to send the coarse to waste and the screen middlings and SAG mill pebbles to be sent either to be crushed and send for heap leaching, crushed and sent to SAG mill (see Figure 11).

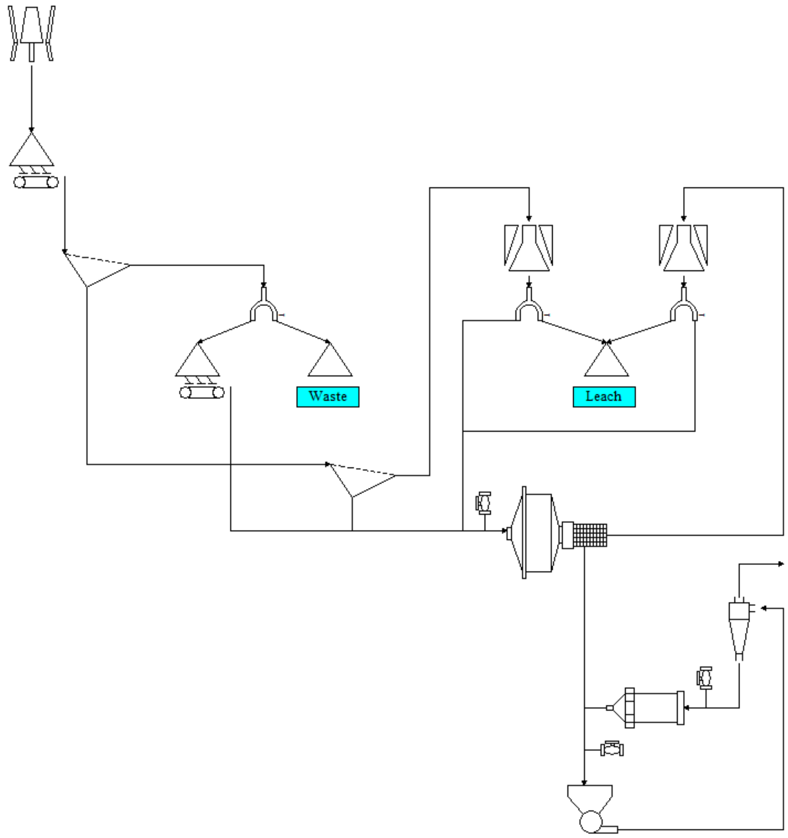


Figure 11 - Flexible circuit process flow diagram.

The process flow diagram was influenced by the envisaged layout of the plant (see Figure 12). During this process design alterations were required confirming the hypothesis that flowsheet design cannot be locked in until layout implications are carefully considered. Therefore there exists a need to consider feasibility of layout early in flowsheet development as even a simplistic layout design can highlight constructability / maintainability / operability / controllability issues. The layout assumed a conventional gyratory primary crusher with coarse ore stockpile prior to screening. Multiple conventional screening units (grizzly's and banana) because no existing double-deck screen was able to perform at the maximum required duty (3-4000 t/h). The fines stockpile could potentially be avoided thus resulting in a more direct flow of ore to the mill. The option of sending either SAG pebbles or screening middlings to leach was also able to be included easily in the design via a flop gate design on the crusher products. Alternatively, fewer conveyors could be used if it is possible to place the waste ore storage beside the lump ore and use a shuttle conveyor to provide the waste rejection.

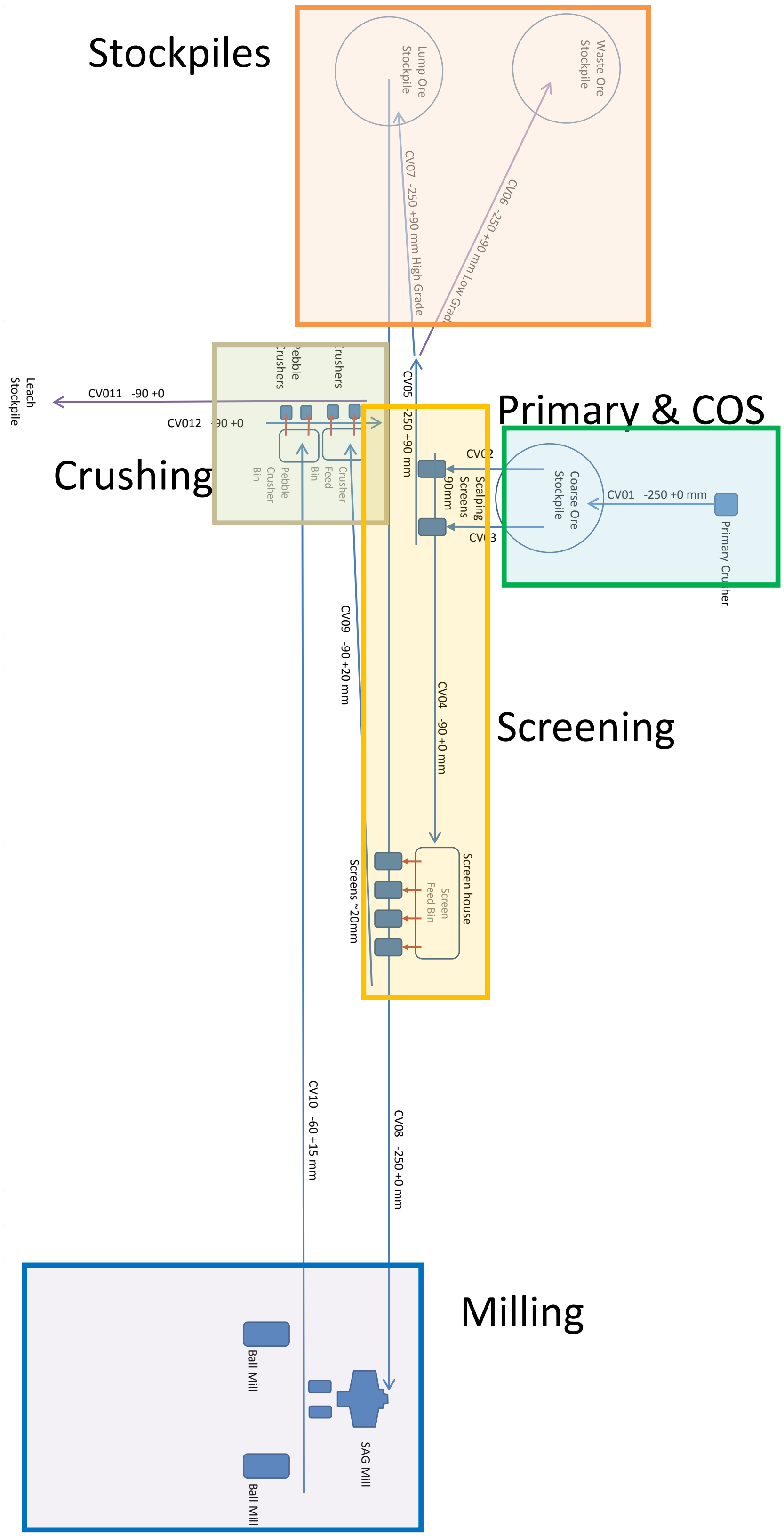


Figure 12– Envisaged circuit layout.

CONCLUSION

Grade Engineering is a strategy that can greatly improve the economics of a mine by taking advantage of preferential grade-by-size deportment characteristics or via differential blasting for grade strategies. These strategies combine to send an altered feed size distribution to the comminution circuit. These feeds have the potential to add significant variability to the process which can be effectively addressed. Comminution circuits with SAG mills installed have the potential to be greatly affected by these changes because of their reliance on coarse material to maintain the ore-load in the mill. Blending and pre-crushing strategies can be employed to reduce the variability and allow the Grade Engineering circuit to be simply added to the front end of the comminution circuit. However, this paper introduces a strategy that can potentially add value by allowing processing flexibility and increased controllability by incorporating the Grade Engineering circuit intimately within the comminution circuit. A flowsheet was developed and modified after careful design of the equipment layout. This circuit allows the crushing or removal of near-size material prior to milling and independent feeding of coarse and fine products from the screening circuit. Rock load within the SAG mill can be controlled via the coarse ore stockpile, and the impact of SAG milling on ball milling performance can be controlled by changing the feed rate of fine material and the quantity of screen middling sent to the mill.

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REFERENCES

Access Economics, (2008). Global commodity demand scenarios. A report prepared by Access Economics for the Minerals Council of Australia.

AusIMM bulletin, (2015). A step change in mining productivity. Retrieved form https://www.ausimmbulletin.com/feature/a-step-change-in-mining-productivity/

Ballantyne, G.R., & Powell, M.S., (2014). Benchmarking comminution energy consumption for the processing of copper and gold ores. *Minerals Engineering 65,* 109-114.

Bamber, A.S., (2008a). Integrated mining, preconcentration and waste disposal systems for the increased sustainability of hard metal mining. Published PhD Thesis, University of British Columbia.

Bamber, A.S., Klein, B., Pakalnis, R.C., Scoble, M.J., (2008b). Integrated mining, processing and waste disposal system for reduced energy and operating costs at Xstrata Nickel's Sudbury Operations. Mining Technology, v 117, n 3, 142-153 pp.

Bamber, A.S., Klein, B., Stephenson, M., (2006a). A methodology for mineralogical evaluation of underground pre-concentration systems and a discussion of potential process concepts, P*roceedings XXXIII International Mineral Processing Congress.* Istanbul, Turkey, 253-258 pp.

Bamber, A.S., Klein, B., & Scoble, M.J., (2006b). Integrated mining and processing of massive sulphide ores, *Proceedings, 39th Annual General Meeting of the Canadian Mineral Processors.* Ottawa, 181-198 pp.

Bowman, D.J., & Bearman, R.A., (2014). Coarse waste rejection through size based separation. *Minerals Engineering, v 62,* 102-110 pp.

Bearman R.A., (2012). Step change in the context of comminution, Keynote Paper: Comminution 2012. *Minerals Engineering, v 43–44*, 2–11 pp.

Carrasco, C., Walters, S.G., Keeney, L., (2015). Development of a novel methodology to characterise preferential grade by size deportment and its operational significance. Submitted to Physical Separation Conference, Falmouth, UK.

Carrasco,C., Keeney,L., Walters,S., (2014). Development of geometallurgical laboratory tests to characterise metal preconcentration by size. Proceedings XXVII International Mineral Processing Congress. Santiago, Chile, Chapter 14, 1-21 pp.

Carrasco,C. (2014). Integrating Grade Engineering® and Process Automation for improving Mining Productivity. RHD Conference Sustainable Minerals Institute (SMI), University of Queensland.

Carrasco,C., (2013). Development of Geometallurgical Tests to Identify, Rank and Predict Preferential Coarse Size by Size Au Deportment to Support Feed Preconcentration at Telfer Au-Cu Mine, Newcrest Western Australia. Published Mphil Thesis, University of Queensland, Australia.

CRCORE, (2015).Grade Engineering. Retrieved from http://www.crcore.org.au/images/docs/gradeengineering.pdf

CRCORE, (2015b). Site Studies. Retrieved from http://crcore.org.au/site-studies

Franks, D., Brereton, D., Moran, C.J., (2010). Managing the cumulative impacts of coal mining on regional communities and environments in Australia. Impact Assessment and Project Appraisal, v 28, 299–312 pp.

Logan, A., Krishnan, N., (2012). Newcrest technology step change. International Mineral Process Conference Proceedings. New Delhi, India, 3025-3037 pp.

Mining Magazine., (2014). Engineering Productivity. Retrieved from http://issuu.com/aspermontmedia/docs/mining-magazine-sept-2014/37?e=0/9233318, 34-37 pp.

Napier-Munn, T., Morrell, S., Morrison, R., Kojovic, T., (1996). Mineral comminution circuits: their operation and optimisation. JKMRC University of Queensland, Brisbane.

Norgate, T., Haque, N., (2010). Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production, v 18*, no 3, 266-274 pp.

Norgate, T., Jahanshani, S., (2010). Low grade ores - smelt, leach or concentrate? Minerals Engineering, v 32, 65-73 pp.

Norgate, T.E., Jahanshani, S.,Rankin, W,J., (2007). Assessing the enviromental impact of metal production processes. *Journal of Cleaner Production, v 15*, no 8-9, 838-848 pp.

Prior, T., Giurco, D., Mudd, G., Mason, L., Behrisch, J., (2012). Resource depletion, peak minerals and the implications for sustainable resource management. Global Environmental Change, v 22, no 3, 577-587 pp.

Topp, V., Soames, L., Parham, D., Bloch, H., (2008). Productivity in the mining industry: measurement and interpretation. Productivity Commission Staff Working Paper.